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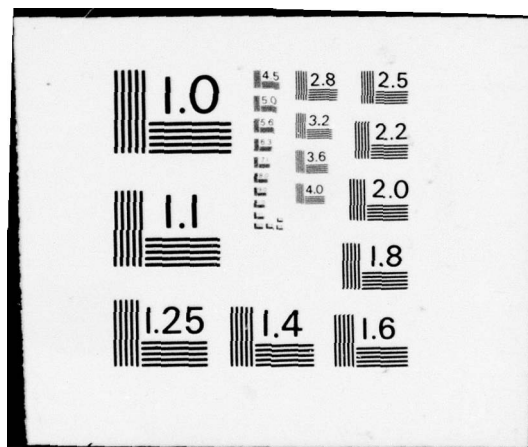
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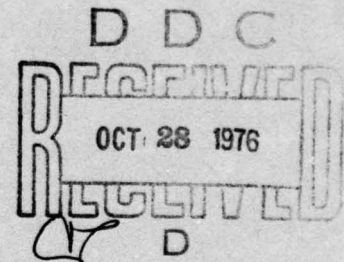
AIRBORNE SEA ICE THICKNESS PROFILING
USING AN IMPULSE RADAR

Rexford M. Morey



June 1975

FINAL REPORT



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16. Abstract The remote measurement of sea ice thickness from a mobile platform has been a goal of researchers and organizations, such as the U.S. Coast Guard, for many years. Ice thickness data is needed over large areas for icebreaker operation and navigation. The objective of this contract is to evaluate a successful ground-based sea ice profiling radar when adapted to a helicopter platform. The electronic and recording equipment were mounted in a small helicopter and the radar antenna was slung on a rope 14 m. below the helicopter. The thickness of fresh water ice and sea ice was successfully measured in the Canadian Arctic near Inuvik, N.W.T. Over 50 km. of first-year sea ice were continuously profiled. The ice thickness varied from 0.5 m. to 2 m. and the wind-swept snow cover varied from zero to 0.3 m. In the traverse mode, sea ice thickness was continuously measured at an altitude of 40 m. and a speed of 65 km/hr. Theoretical considerations and experimental results are given.		
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INTRODUCTION

The remote measurement of ice thickness from a mobile platform has been a goal of researchers and organizations, such as the U. S. Coast Guard, for many years. Ice thickness data is needed over large areas for icebreaker operation and navigation and for the mapping of impediments to traffic in shipping lanes.

This report describes an experimental program for the measurement of ice thickness using a helicopter-borne ice thickness profiler. The thickness of fresh ice and sea ice was successfully measured in the Canadian Arctic near Inuvik, N.W.T. The ice thickness profiler is a high resolution short pulse radar developed by Geophysical Survey Systems, (GSS) Inc. This unique radar is called the Electromagnetic Subsurface Profiling (ESP) System. GSS has been profiling the thickness of sea ice from the surface of the ice for three years. Over 4000 km. of sea ice surveys have been performed in the Arctic.

The purpose of the program described in this report was to adapt the existing ground-based ESP ice profiling equipment to a helicopter platform and to perform a series of flight tests over ice to determine the effectiveness of the ESP radar in measuring ice thicknesses.

A rented Bell 206 helicopter, with a belly mounted cargo hook for supporting the antenna, was used for the flight tests. Measurements were made with the helicopter rising vertically to an altitude of 60 m. In the traverse mode, the thickness of first-year sea ice was accurately measured at an altitude of 40 m. and a speed of 65 km/hr. Sea ice thickness varied from

0.5 m. to 2 m. and averaged about 1.6 m. Snow cover varied from zero to 0.3 m.

BACKGROUND

Ice thickness data is required for the mapping of potential hazards and impediments to traffic in ice covered shipping lanes. Interest in ice thickness data has increased substantially in the last few years due to favorable economic forecasts for shipping both in Arctic waters and Northern domestic waterways.¹ Timely ice thickness data is important to icebreaker operation and navigation. Another recent area of interest is trafficability on ice in the Arctic. Oil exploration in the Arctic often requires the movement of personnel and equipment across ice, both offshore and on frozen lakes and rivers. The safe performance of over-ice transportation requires a continuous, accurate profile of ice thickness along the routes to be travelled.²

Until recently the only precise thickness measurements that could be obtained were by drilling a hole in the ice and making a direct measurement. Various electromagnetic techniques have been tried, with unsatisfactory results.³ A distinction must

¹Welsh, J.P., and Erlich, N.A., 1973. Ice and Icebreakers; Presented at Advanced Concepts and Techniques in the Study of Snow and Ice Resources, Monterey, Calif. December 2-6, 1973.

²Orange, A.S., 1973. "ESP Saves Money in Arctic by Finding Ice Roads for Moves", Oilweek, 6 August 1973.

³Adey, A.W., 1970. A Survey of Sea-Ice Thickness Measuring Techniques CRC Report No. 1212, Communications Research Ctr., Dept. of Communications, Ottawa, Ontario, Canada.

be made here between lake and sea ice. Several investigators have developed airborne systems that have promise in measuring lake ice thickness.⁴ However, attempts to remotely measure sea ice thickness have been unsuccessful. An exception may be an extension of the equipment developed by Geophysical Survey Systems, Inc.⁵ This technique, known as Electromagnetic Subsurface Profiling (ESP) presently operates from the surface of the ice, but not in direct contact with the surface.

The reason for this mode of operation is the purpose for which the equipment was originally developed. GSS, Inc. was formed about 5 years ago to develop and use an impulse radar (ESP) system for detecting objects and interfaces in soil. Because of the resolution needed in precisely locating underground pipes and utilities, the system was operated near the surface (within 6 inches) of the ground. There was no intent on using the technique to measure ice thickness. However, a task in a contract with the Office of Naval Research required evaluating the ESP system under Arctic conditions.⁶ During these evaluations at Barrow, Alaska it became apparent that the system could accurately measure the thickness of sea ice and

⁴Vickers, R.S., Heighway, J., and Gedney, R., 1973. Airborne Profiling of Ice Thickness Using a Short Pulse Radar: Presented at Advanced Concepts and Techniques in the Study of Snow and Ice Resources, Monterey, Calif. December 2-6, 1973. NASA TMX-71481.

⁵Campbell, K.J., and Orange, A.S., 1974. A Continuous Profile of Sea Ice and Freshwater Ice Thickness by Impulse Radar. Polar Record, Vol. 17, No. 106, 1974, p. 31-41.

⁶Bertram, A.L., Campbell, K.J., and Sandler, S.S., Characteristics of Sea Ice, Lake Ice, and Permafrost Using an Impulse Radar System, Technical Report No. 008-72, Contract No. N00014-71-C-0392; GSS, Inc., May 1972.

lake ice. Since then GSS has performed operational surveys covering 4000 km. of route at several locations in the Canadian Arctic for oil companies. During some of these surveys the radar antenna was raised 2 m. off the surface of the ice. The ice/water interface was still detected. For this reason and from other experiments with the antenna raised above the ground, GSS felt confident that it was possible to measure sea ice thickness using the ESP system mounted in a helicopter. The results of the program described herein demonstrated the feasibility of this approach.

The goals of the experimental program were to determine 1) how well the system operates from a helicopter, 2) what altitudes can be flown and still detect the ice/water interface, 3) what effect forward speed has on resolution, and 4) other potential operational problems.

PROPERTIES OF SNOW, ICE AND WATER

The electromagnetic (EM) properties of water in its various physical state has been reported by many investigators.⁷ These properties depend principally upon frequency, temperature, density, and the concentration of impurities. The radar used on this program transmits a short pulse which has a broad frequency spectrum centered at 100 MHz. Of interest then is the dielectric constant and attenuation of snow, ice and water at 100 MHz. The dielectric constant determines the velocity of propagation of an EM wave and is given by:

$$v = c \left(\frac{1}{\sqrt{\epsilon_r}} \right) \text{ m/sec.} \quad (1)$$

⁷Hoekstra, P. and Capillino, P., and 1971. Dielectric Properties of Sea and Sodium Chloride Ice at VHF and Microwave Frequencies. J. Geoph. Res. 76, 20:4922-4931.

Therefore, the time for a pulse to propagate through a layer "d" meters thick is

$$t = \frac{d}{v} = \frac{d\sqrt{\epsilon_r}}{c} \text{ sec.} \quad (2)$$

where

$$\begin{aligned} c &= 3 \times 10^8 \text{ m/sec} \\ d &= \text{thickness in meters} \\ \epsilon_r &= \text{relative dielectric constant} \end{aligned}$$

For low-loss dielectric materials, the reflection coefficient between two layers of dielectric constants ϵ_1 and ϵ_2 is given by

$$R_{12} = \frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}} \quad (3)$$

and the transmission coefficient by

$$T_{12} = \frac{2}{1 + \sqrt{\epsilon_2} / \sqrt{\epsilon_1}} \quad (4)$$

Table 1 shows some representative values for dielectric constant and attenuation for the materials of interest at 100 MHz. As can be seen unfrozen water has the highest dielectric constant and therefore, the coefficient of reflection will be greatest at a water interface.

The dielectric constant of snow is primarily a function of snow density; snow being a mixture of ice crystals and air. The density of snow varies from 0.1 to 0.7 grams/cm³. (Pure ice has a density of 0.916 gms/cm³.) Therefore, the dielectric constant of snow varies from 1.2 (0.1 gms/cm³) to 2.5 (0.7 gms/cm³). Also,

TABLE 1. DIELECTRIC CONSTANT AND ATTENUATION AT 100 MHZ

<u>Material</u>	<u>Approximate Dielectric Constant ϵ_r</u>	<u>Approximate Attenuation (db/meter)</u>
Air	1	0
Fresh Water	81	0.41
Sea Water	81	326
Fresh Water Ice (-12°C)	3.2	0.05
Sea Ice	3.5 to 10	1 to 10
Freshly Fallen Snow (-20°C)	1.2	0.03
Hard Packed Snow (-6°C)	1.5	0.04

snow is a low loss dielectric material, as is fresh-water ice. This means that EM waves propagate through snow and fresh-water ice with very little attenuation.

Sea ice is a different matter. Because liquid inclusions of brine are entrapped in its ice matrix, sea ice differs from fresh water ice in physical behavior. This difference is strongly evident in the dielectric properties of the two ice forms. The amount of brine entrapped in the ice depends on the rate of ice growth, and for young sea ice it may reach salinities as high as 20 parts per thousand. Under the influence of gravity brine drainage occurs through interconnecting channels in the sea ice matrix, and under the influence of temperature gradients brine pockets diffuse through the ice to the warm side of the ice. Because the amount of liquid water in sea ice changes with temperature, the dielectric properties (and attenuation) of sea ice are strongly temperature dependent. Likewise, the EM properties of sea ice are strongly frequency

dependent. GSS has found through repeated experimentation that the frequency spectrum of its radar system provides the best compromise of resolution and penetrability for sea ice profiling. Higher frequencies cannot penetrate sea ice due to the high attenuation rate (3 to 4 orders of magnitude larger than that of fresh-water ice).

At this point a few calculations will show the magnitudes of the signals reflected from the top and bottom surfaces of ice and snow. These magnitudes are those that the signals assume in air, after leaving the snow. R_s , R_i , and R_w are the magnitudes of the signals reflected from the top surface of the snow, ice, and water, respectively, and are functions of, 1) the rates of attenuation in, and depths of, the snow and ice layers, and 2) the boundary reflection and transmission coefficients.

$$R_s = R_{as} \quad (6)$$

$$R_i = T_{as} R_{si} T_{sa} 10^{-(A_s 2d_s)/20} \quad (7)$$

$$R_w = T_{as} T_{si} R_{iw} T_{is} T_{sa} 10^{-(A_s 2d_s + A_i 2d_i)/20} \quad (8)$$

where

d_s and d_i = the depth of snow and ice (meters)

A_s and A_i = the rates of attenuation in snow and ice (db/meter).

R_{as} , R_{si} , T_{as} , etc., are the magnitudes of the boundary reflection and transmission coefficients. They are functions of the dielectric properties of the materials on either side of the boundary (Equations 3 and 4). For our purposes we will express R_s , R_i , etc., in decibels where, for example

$$R_i(\text{db}) = 20 \log_{10} R_i \quad (9)$$

Using dielectric constants of 1.5 for snow and 4 for sea ice for calculating the reflection coefficients, the values to be expected are:

Air/Snow Interface	R_{as}	=	10%	=	-20 db
Air/Ice Interface	R_{ai}	=	33%	=	-9.5 db
Snow/Ice Interface	R_{si}	=	24%	=	-12.4 db
Ice/Water Interface	R_{iw}	=	64%	=	-3.9 db

These values assume plane parallel layers of snow and ice. Surface roughness will modify the numbers. Note that the strongest reflection occurs at the ice/water boundary; the experimental results also show this effect. Sea ice can be lossy, further reducing the reflection from the ice/water interface. For example, very lossy sea ice with an attenuation rate of 10 db/m will reduce the reflection coefficient, R_w , by 20 db. for every meter of ice. However, GSS has not encountered any sea ice from which a reflection at the water boundary was not detected.

RADAR EQUATIONS

This section deals with the radar equation for the propagation of electromagnetic signals from an airborne antenna and the resultant scattering from an air/ice interface and an ice/water interface. The effectiveness of an ice profiling radar is limited by the maximum range to, and the probing distance in, sea ice. The probing depth is determined by the radar system limitations and by the total propagation loss. Electromagnetic signals are attenuated with distance due to geometric spreading as the energy travels away from the

transmitting antenna and due to energy absorption in the ice as the signal passes through it. Two-way propagation, including reflection from smooth ice boundaries, can be described by the following radar equation.⁸

$$\frac{P_r}{P_t} = \underbrace{\frac{G_t G_r \lambda_o^2 L_t L_r}{(4\pi)^2 [2(h+d)]^2}}_{\text{spreading loss}} \times \underbrace{\frac{1}{L_s}}_{\text{absorption loss}} \quad (10)$$

where

- P_r = received power in watts
- P_t = transmitted power in watts
- G_t = transmitting antenna gain
- G_r = receiving antenna gain
- λ_o = free space wavelength in meters
- h = antenna height above ice surface in meters
- d = thickness of ice in meters
- L_t = power transmission factor at air/ice interface
- L_r = power reflection coefficient at interface
- L_s = two-way absorption through d meters of ice

The power reflection coefficient is given by

$$L_r = \left| R_{12} \right|^2 = \left| \frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}} \right|^2 \quad (11)$$

and the two-way transmission coefficient by

$$L_t = \left| \frac{4 \sqrt{\epsilon_2 / \epsilon_1}}{\left(1 + \sqrt{\epsilon_2 / \epsilon_1} \right)^2} \right|^2 \quad (12)$$

⁸Wait, J.R., 1971. Electromagnetic Probing in Geophysics. The Golem Press, Boulder, Colorado. Page 335.

The two-way absorption, L_s , may be expressed in decibels by

$$L_s = 2Ad \quad (13)$$

where A is the rate of attenuation in ice in db/m.

The operating frequency of a radar system is a critical system parameter and is arrived at through a compromise of several conflicting factors. As an example the absorption loss of ice increases with increasing frequency. Thus the depth of penetration will increase with decreasing frequency. However, the range resolution (or depth measurement accuracy) improves with increasing frequency. Also, antenna size and therefore, antenna gain (G) are determined by the operating frequency. The physical antenna aperture is generally determined by portability and field surveying constraints. The ice profiling radar uses a single transmitting and receiving antenna which has an aperture area of about one square meter. The free space antenna gain over an isotropic radiator is about 1.5. The output of the transmitter is a short gaussian shaped pulse with a 50% pulse width of about 3 nanoseconds (ns). Therefore, the pulse has a continuous, constant amplitude frequency spectrum from DC to 150 MHz (-3db point). The antenna tends to bandlimit the transmitter output, reducing the energy at the lower frequencies. Thus, the frequency spectrum of the radiated pulse is centered at 100 MHz and the -3db points are about 50 Mhz and 150 MHz.

Radar system limitations can be summarized by the system "Performance Figure" (P.F.) as follows:

$$P.F. = \frac{\text{radiated peak power}}{\text{minimum detectable received signal power}} \quad (14)$$

Equation (10) can be expressed in decibels as the Total Propagation Loss (T.P.L.) which must be less than the Performance Figure for the detection of an ice/water interface.

$$P.F. \geq T.P.L. = 10 \log_{10} \left[\frac{(4\pi)^2 [2(h+d)]^2}{G^2 \lambda_o^2 L_t L_r} \right] + 2Ad \quad (15)$$

Note that Equation (15) assumes the idealized case of smooth, flat, horizontal reflecting surfaces. However, many ice conditions will include surfaces that are too rough for coherent, specular reflection. In this case the approximate equation is

$$T.P.L. = 10 \log_{10} \left[\frac{(4\pi)^3 (h+d)^4}{G^2 \lambda_o^2 L_t L_r \sigma} \right] + 2Ad \quad (16)$$

where σ is the radar cross section which is the area of the "first Fresnel zone"⁹ or

$$\sigma \approx \pi \lambda_o (h+d)/2 \quad (17)$$

Substituting (17) in (16),

$$T.P.L. = 10 \log_{10} \left[\frac{128\pi^2 (h+d)^3}{G^2 \lambda_o^3 L_t L_r} \right] + 2Ad \quad (18)$$

Equations (15) and (18) are plotted in Figure 1 for the ice profiling radar used in these experiments, where $G = 1.5$, $\lambda_o = 3$ meters, $\epsilon_{ice} = 3.2$, and the ice thickness is 2 meters. The approximate Performance Figure for the radar is 75 db. The flight tests indicated that reflections from the ice surface were undetectable at an antenna altitude greater than about 40 meters. However, the ice/water interface was still visible.

⁹Cook, J.C., 1974. Status of Ground-Probing Radar. Proceedings of Engineering Foundation Conference on "Subsurface Exploration for Underground Excavation and Heavy Construction". American Society of Civil Engineers, New York.

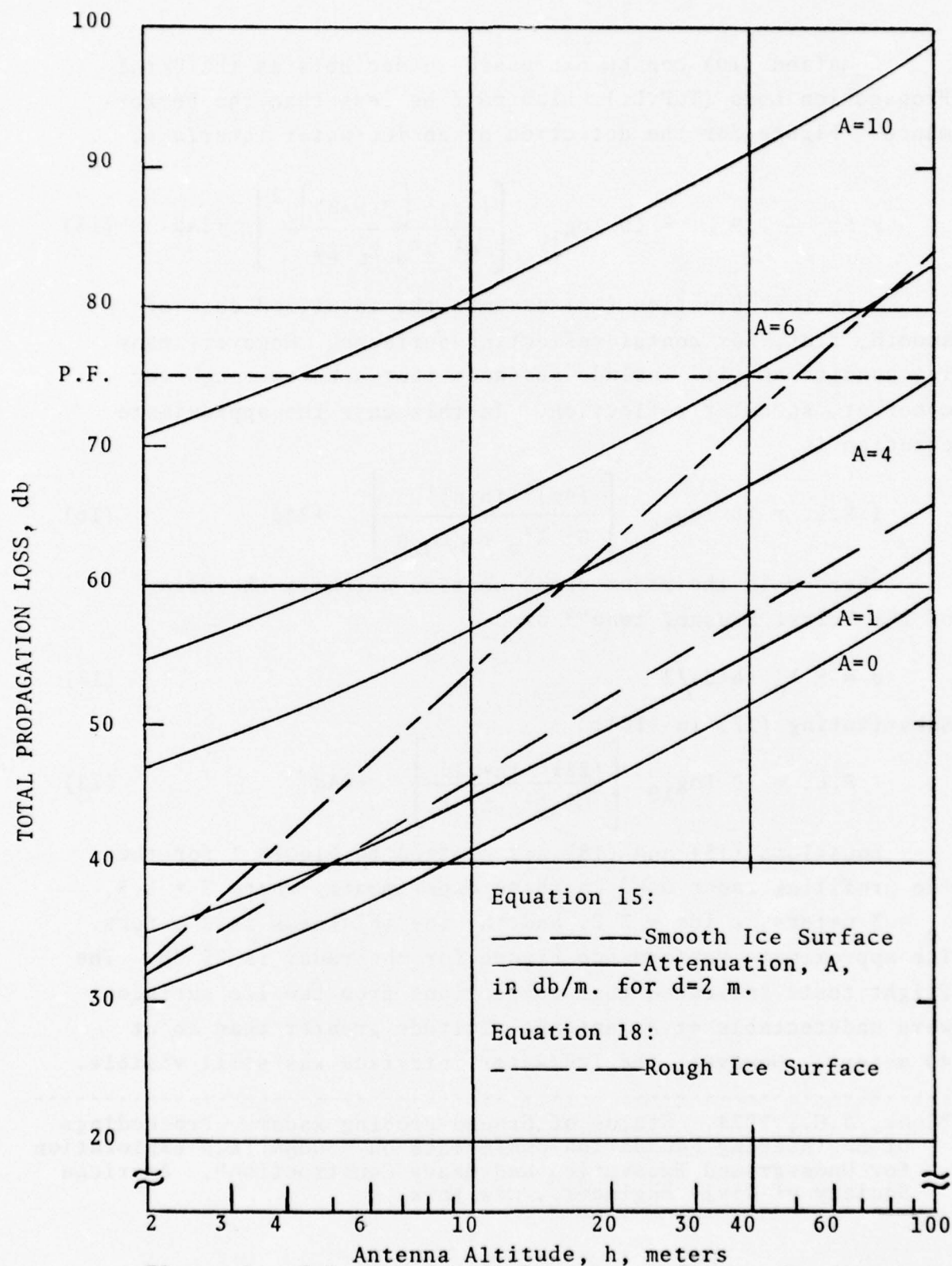


Figure 1. Calculated Path Loss vs. Reflector Range.

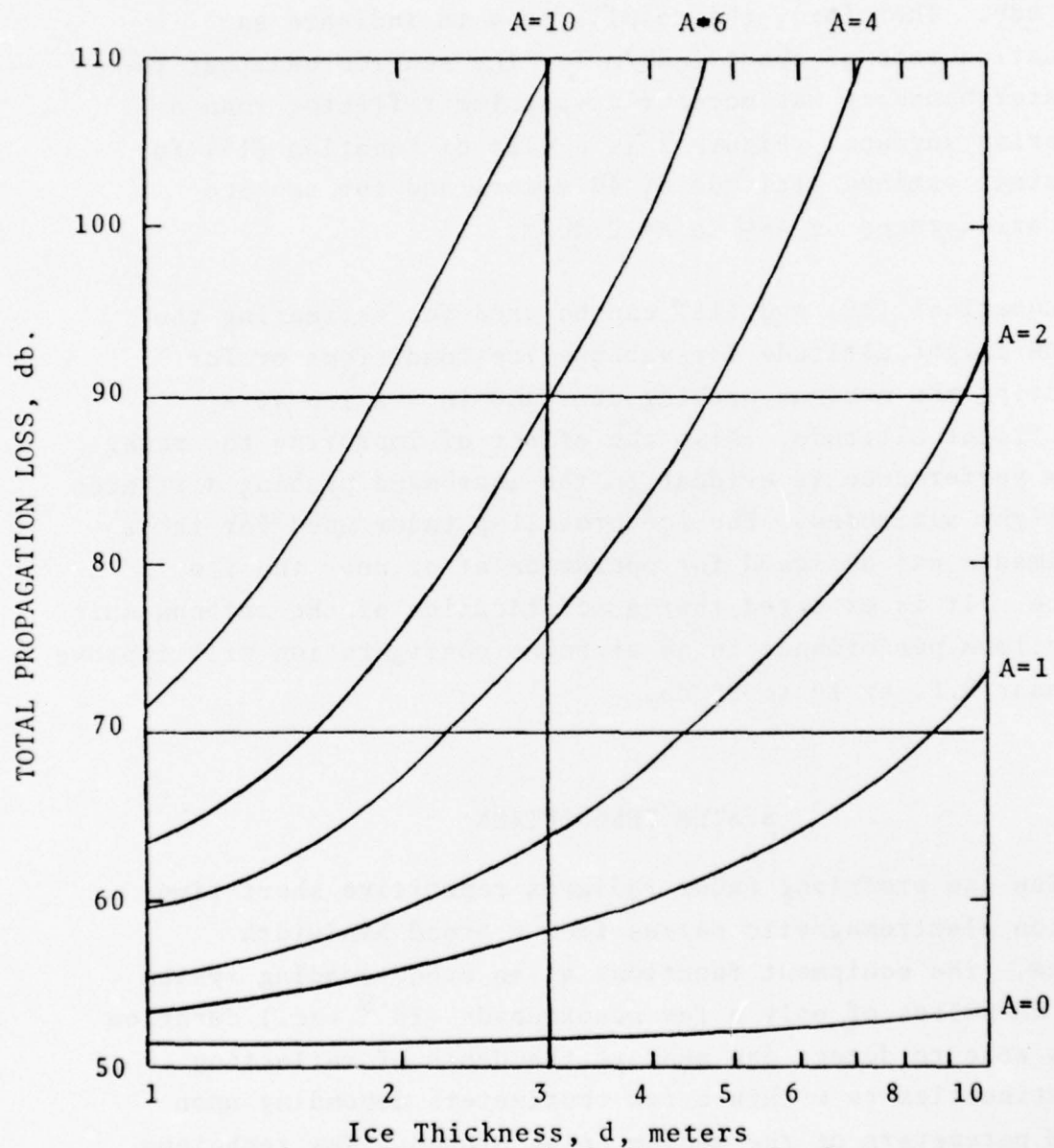
Evidently, there was a fair amount of scattering at the air/ice interface. This was partly due to the wind blown snow cover which varied in thickness. In all cases the ice/water reflection was stronger than the air/ice reflection; for example, the difference at an altitude of 10 meters was about 9db. Therefore, the results seem to indicate an attenuation rate of about 1 db/m for the sea ice and that the ice/water boundary was more of a specular reflector than a scattering surface. Figure 2 is a plot of Equation (15) for a constant antenna altitude of 40 meters and for sea ice attenuation rates of $A=0$ to $A=10$ db/m.

Equations (15) and (18) can be used for estimating the maximum flight altitude for various ice conditions or for predicting the maximum probing distance in sea ice at a given flight altitude. Also the effect of improving the radar system performance is evident in the increased probing distances and flight altitudes. The ice profiling radar used for these experiments was designed for operation at or near the ice surface. It is expected that a modification of the antenna unit for optimum performance in an airborne configuration will improve the radar P.F. by 10 to 20 db.

SYSTEM DESCRIPTION

The ice profiling radar radiates repetitive short-time-duration electromagnetic pulses from a broad bandwidth antenna. The equipment functions as an echo sounding system using EM pulses of only a few nanoseconds (10^{-9} sec.) duration and is able to detect and measure the depth of reflecting discontinuities to within a few centimeters depending upon the EM parameters of the medium being probed. The technique can be considered as the electromagnetic equivalent of the

Attenuation, A , of Sea Ice in db/m.



Assumptions: Flat Smooth Reflecting Surface
(Equation 15) and $h = 40$ m.

Figure 2. Calculated Path Loss vs. Ice Thickness

single trace acoustic profiling methods used for marine sub-bottom profiling. In practice, continuous profiling is done by towing an antenna behind a small vehicle or slinging it from a small helicopter containing the electronic equipment. Real-time profile data are displayed graphically on a strip-chart recorder. The data may also be recorded on magnetic tape for later processing and playback. The echo or reflection from the air/ice and ice/water interface is recorded, and the travel time from the ice surface to the water boundary and back is measured. Once the velocity of propagation within the ice is known, either from a knowledge of the electrical properties or from direct mechanical calibration by measurement of ice thickness, then the travel time can be converted directly to ice thickness.

Figure 3 is a photograph of the ice profiling radar. The system is composed of 1) a radar set, 2) a 30-m control cable,

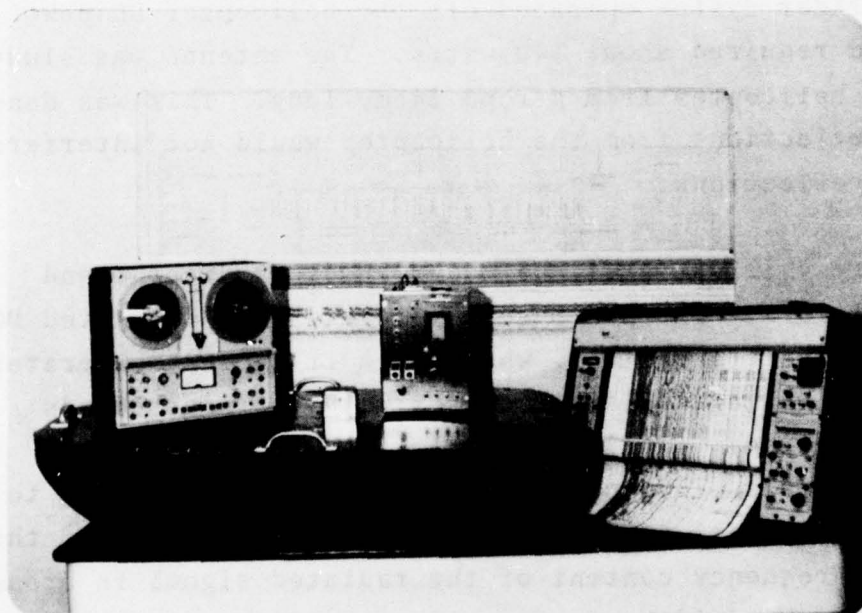


FIGURE 3. ICE PROFILING RADAR

3) an antenna-transceiver unit, 4) a graphic recorder, and 5) a magnetic tape recorder (optional). (In the photograph the tape recorder and radar set are on top of the antenna.) The radar set is housed in a cubic metal case approximately 30 cm on a side, which contains all the control electronics, including the radar receiver, signal processing circuits, control dials, and a monitor oscilloscope. The radar set operates off a 12 volt battery and draws about 1.5 amp.; it weighs about 13 kg. The control cable connects the radar set to the antenna-transceiver unit. The antenna-transceiver unit, which weighs about 32 kg., contains an antenna for transmission and reception, the transmitter and the high frequency components of the receiver. Thus, the control cable carries only low frequency audio signals. The graphic recorder weighs about 31 kg and the tape recorder about 22 kg. All the equipment except the antenna-transceiver unit were mounted in the helicopter.

The radar system operated off the helicopter DC power supply and required about 340 watts. The antenna was slung under the helicopter from a rope 14 m. long. This was done so that reflections from the helicopter would not interfere with ice reflections.

Figure 4 illustrates the radar in block diagram and functional form. The power supply furnishes a regulated DC voltage to the transmitter, which when triggered, generates a base band voltage pulse of approximately 3 nanoseconds in time duration. (It is important to note that this is a voltage impulse, not pulsed CW). This pulse is shaped to quasi-gaussian form and radiated into space by means of the antenna. Frequency content of the radiated signal is broad-band, with a bandwidth of approximately 100 MHz in the low

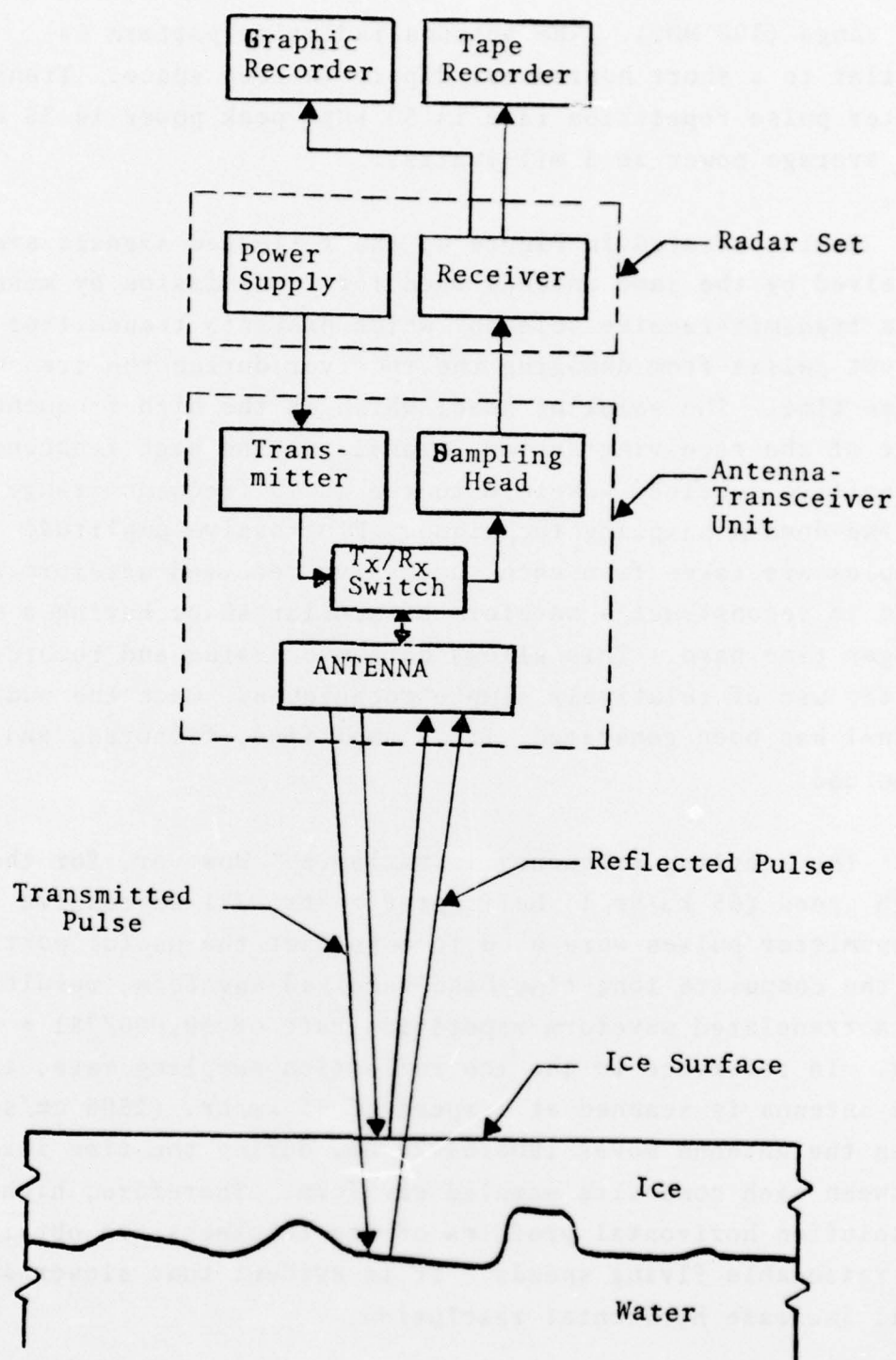


Figure 4. Block Diagram of Ice Profiling Radar

VHF range (100 MHz). The antenna radiation pattern is similar to a short horizontal dipole in free space. Transmitter pulse repetition rate is 50 KHz, peak power is 35 watts, and average power is 5 milliwatts.

As illustrated in Figure 4, the reflected signals are received by the same antenna used for transmission by means of a transmit-receive selector which prevents transmitter output pulses from damaging the receiver during the transmit pulse time. The sampling head, which is the high frequency part of the receiving system, translates the high frequency repetitive received waveform to the audio frequency range by a time-domain sampling technique. Progressive amplitude samples are taken from each successive received waveform and used to reconstruct a waveform of similar shape having a much longer time base. This allows data processing and recording by the use of relatively simple techniques. Once the audio signal has been generated, it is amplified, filtered, and recorded.

The sampling frequency is variable. However, for the high speed (65 km/hr.) helicopter tests, 781 successive transmitter pulses were used to construct the useful portion of the composite long-time-base received waveform, resulting in a translated waveform repetition rate of $50,000/781 = 64$ pps. In reference to the ice reflection sampling rate, if the antenna is scanned at a speed of 65 km/hr. (1806 cm/sec), then the antenna moves $1806/64 = 28$ cm. during the time interval between each composite sampled waveform. Therefore, high-resolution horizontal profiles of ice thickness are obtainable at reasonable flying speeds. It is evident that slower speeds will increase horizontal resolution.

Profile data is displayed on a graphic recorder identical to those used in marine bottom and subbottom profiling. The input waveform to the recorder sketched in Figure 5A consists of the transmit feed-through pulse, the reflection from the ice surface, and the reflection from the ice/water interface. Note that, whereas the transmitted pulse input to the antenna during the transmit cycle is a short, monopolarity pulse, the filtering effect of the finite-bandwidth antenna and the subsurface media itself results in the sinusoidal appearance of the reflected signal.

The recorder is an intensity-modulated device, with the sweep of the stylus across the chart paper synchronized with the pulse transmitter trigger. Signal amplitudes above a preset threshold level are printed as black but weaker signals remain white. The paper moves as the stylus is swept, producing the profile or section shown in Figure 5B. The dark bands occur at signal peaks (both positive and negative peaks are printed), the narrow white lines being the zero crossing between peaks. The chart paper is calibrated in nanoseconds of time, and therefore it can be also calibrated in terms of ice thickness once the relation between travel time and ice thickness is known.

Since the velocity of propagation in air is a well known constant, the two-way travel time from the antenna to the surface of the ice accurately determines the antenna altitude. Therefore, when flying at a constant altitude, the profile displays the true relationship between ice surface topography and ice bottom topography.

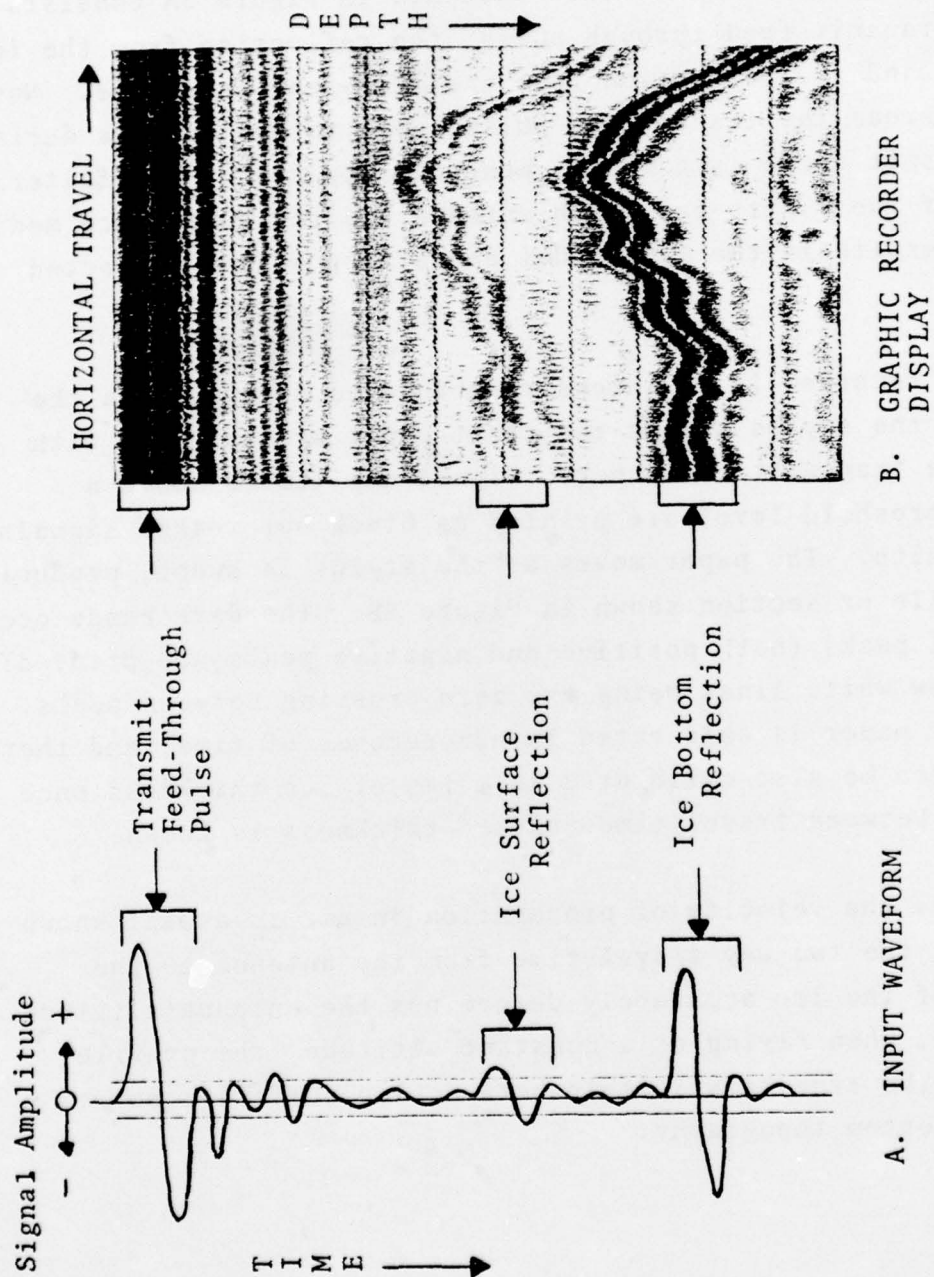


Figure 5. Explanation of Radar Data Presentation

EXPERIMENTAL RESULTS

The experimental work was carried out near Inuvik, N.W.T. and Tuktoyaktuk, N.W.T. in the Canadian Arctic during April 1975. After several trial flights near Inuvik, the system was taken to Tuktoyaktuk for sea ice tests. The flights near Inuvik were over fresh water ice on the Mackenzie River. Figure 6 is a section of data from fresh water ice. In this case the helicopter is descending slowly and moving forward (reading from left to right). The ice/water interface is quite evident. However, the air/ice reflection is just visible above the system background noise. The calculated ice thickness is 1 meter (using $\epsilon_r = 3.2$). No attempt was made to mechanically measure ice thickness. Our experience has shown that using a dielectric constant of 3.2 for fresh water ice results in good agreement with the actual ice thickness.

First-year sea ice exists in the vicinity of Tuktoyaktuk. An attempt to locate multi-year sea ice was unsuccessful. Flight tests were made from Tuktoyaktuk on a line extending NNW 24 km. into the Beaufort Sea. About 16 km. out a refrozen lead was located which ran approximately parallel to the shore line. This lead was crossed several times at a speed of 4 km/hr. The helicopter landed next to the lead for a visual inspection. The refrozen lead was about 60 cm. wide. A typical profile from these tests is shown in Figure 7. The vertical variation in the surface reflection is due to the helicopter changing altitude. Researchers from the Geological Survey of Canada who were augering holes in the sea ice in the vicinity of the flight tests, indicated that ice thickness was between 1.5 and 2 meters. Assuming that the ice surface is flat, then Figure 8 is a reconstructed profile of Figure 7, showing the variation in ice thickness. The ice thickness scale assumes

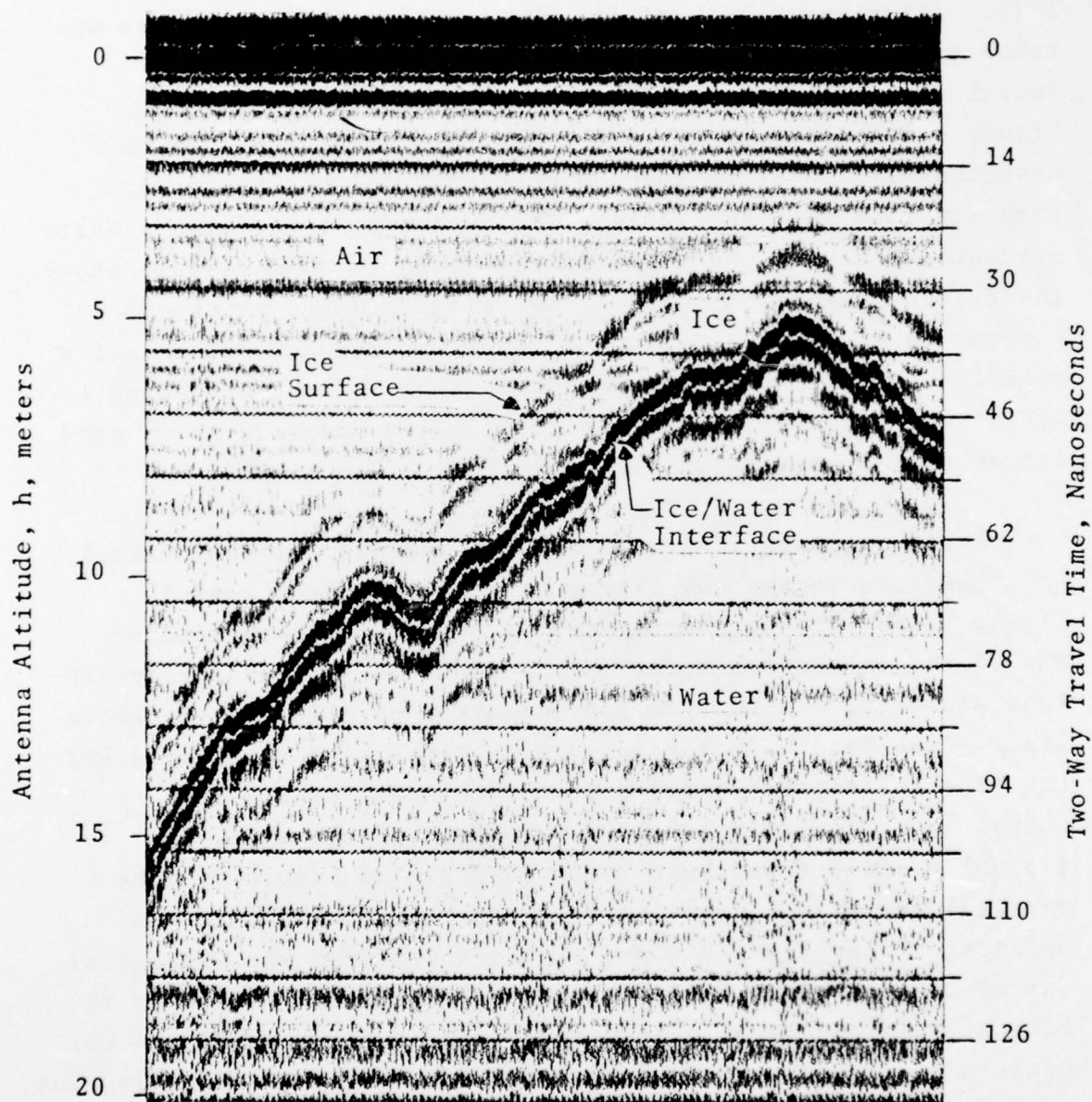


Figure 6. Profile Data: Freshwater Ice, Mackenzie River, Average Ice Thickness 1m.

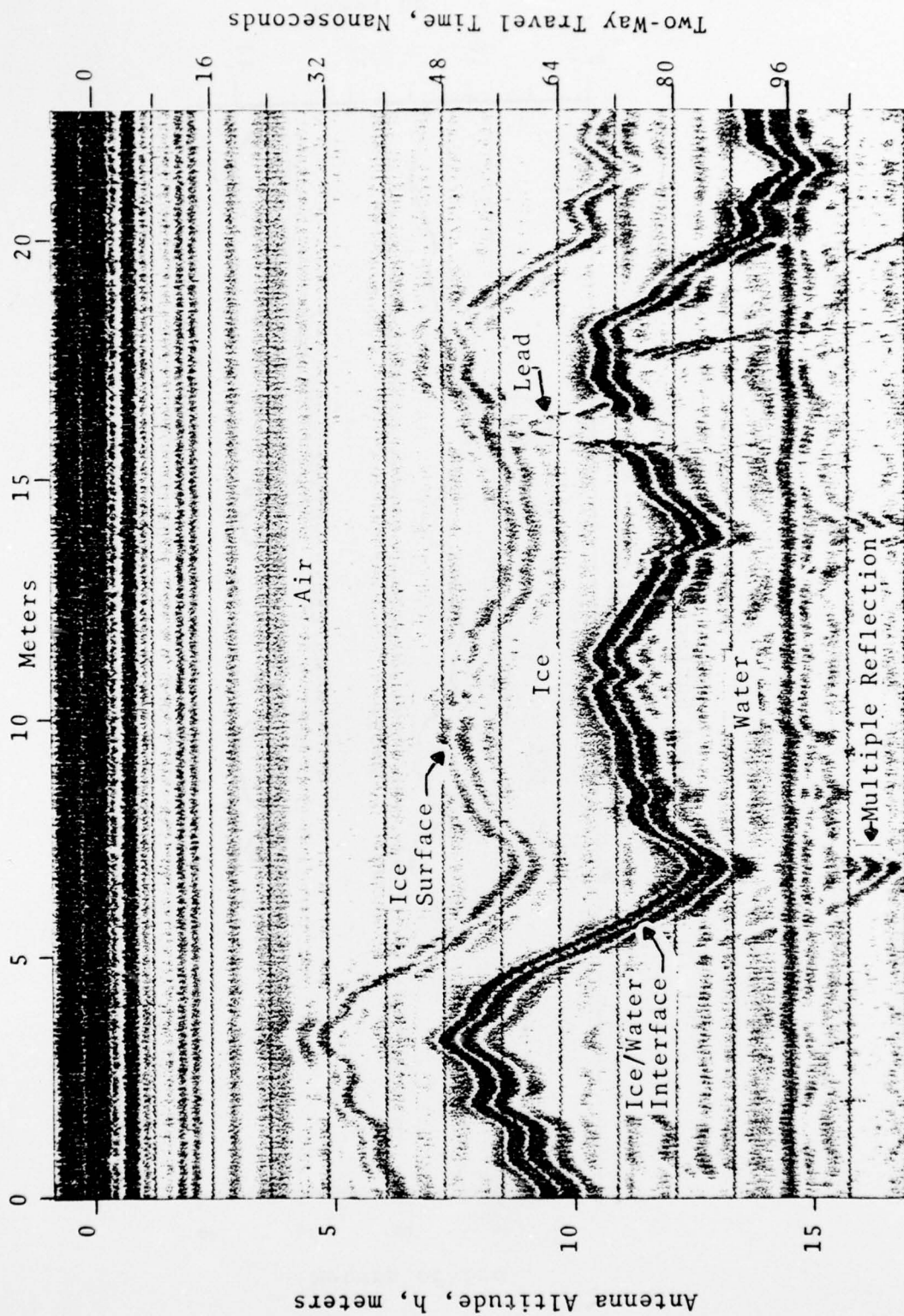


Figure 7. Profile Data: First-Year Sea Ice, Refrozen Lead.

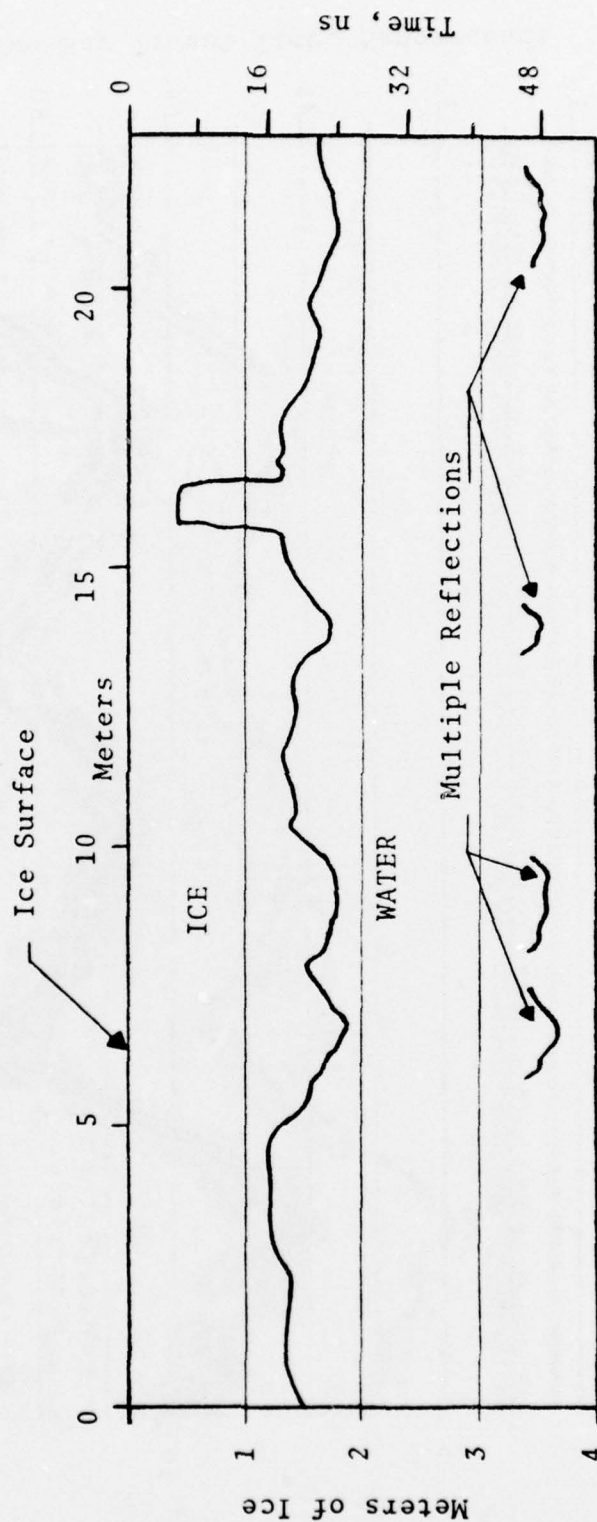


Figure 8. Reconstructed Profile from Figure 7.

a dielectric constant of 4 for the sea ice.

Referring to Figure 7, note the strong multiple reflection between the 6 and 8 meter stations. Also note that the ice is thicker here. This is due to lack of snow cover. Experience has shown that the thickness of snow cover has an effect on ice thickness, since the snow acts as a thermal blanket. The wind swept snow formed wind-rows, whereby the snow thickness varied from zero to 0.3 meters. On all of the profile data, the sections of strong multiple reflections occurred where the ice was thickest. It is difficult to discern a reflection from the top of the snow in the profile data. However, in the vicinity of the refrozen lead (17-19 m.), there is a definite reflector above the ice surface. This was a section where the snow was 0.3 meters thick. The reflection from the bottom of the refrozen lead is 5 to 7 db. weaker than the ice/water reflections elsewhere. Evidently, the narrow width of the lead presents a smaller reflecting surface and the sea ice in the lead is younger and has a higher absorption loss.

At the range of 96 ns. in Figure 7 is a dark band which is continuous across the profile. This is the reflection from the helicopter (the spacing between the antenna and helicopter is 14.6 meters). Note that the helicopter reflection is weaker than the ice/water reflection. The radar cross section of the helicopter is smaller than that of the ice/water boundary.

A relatively high speed (65 km/hr.) traverse, about 16 km. long at an altitude of 45 to 55 meters was made from the refrozen lead to Tuktoyaktuk. An example of profile data in this traverse mode is shown in Figure 9. Sea ice thickness averaged about 1.6 m. and varied from 0.5 m. to 2 m. At an antenna altitude greater than 40 m. the ice surface reflection was difficult to discern; however, the ice/water boundary was still apparent.

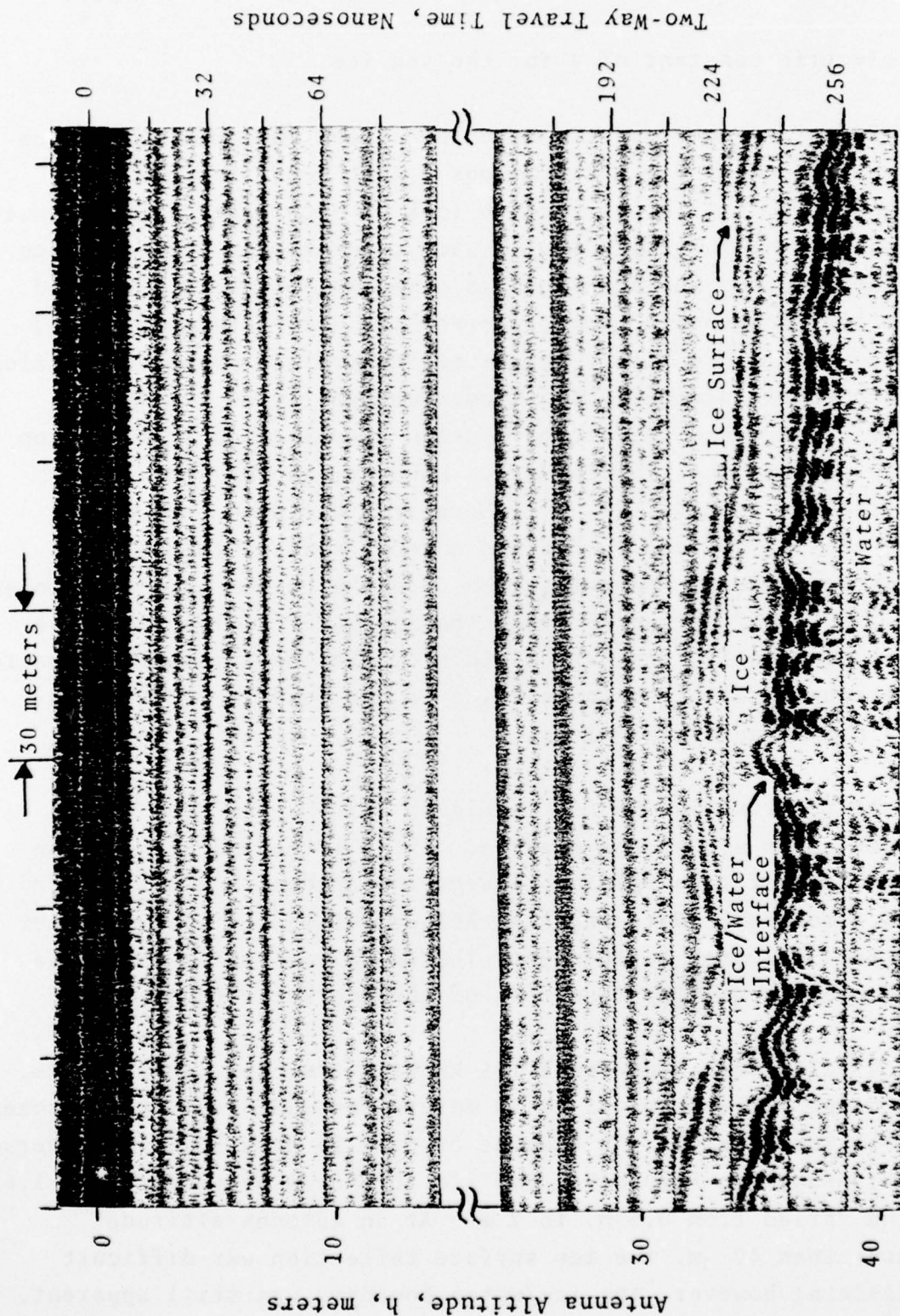


Figure 9. Profile Data: First Year Sea Ice, Helicopter Speed 65 km/hr.

CONCLUDING REMARKS

The experiments demonstrated that the GSS ice profiling radar will operate from a small helicopter and will profile the thickness of first-year sea ice of the type encountered during the tests. Profiles can be taken at reasonable altitudes and speeds. At lower altitudes and slower speeds, greater detail on ice thickness is achievable and small refrozen leads can be detected. Interference from off-axis reflections and varying snow cover did not seem to be a problem. As expected the reflection from the surface of the ice is weaker than that from the bottom of the ice for moderately lossy sea ice.

An antenna configuration has recently been developed that can be mounted directly under the belly of a helicopter. This configuration plus a radar with an improved system Performance Figure should be tried on other types of sea ice, especially multi-year sea ice and keel ice.

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